Assessing exposure to cosmic radiation during long-haul flights

Jean-François Bottollier-Depois[*], Quang Chau[*], Patrick Bouisset[†], Gilles Kerlau[†],
Luc Plawinski[*], and Laurence Lebaron-Jacobs[*]

[*]*Human Health Protection and Dosimetry Division and* [†]*Environmental Protection Division,*
Institute for Protection and Nuclear Safety, BP 6, 92265 Fontenay-aux-Roses, France

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Correspondence:
Jean-François Bottollier-Depois
IPSN - Dosimetry Department, BP 6, 92265 Fontenay-aux-Roses Cedex, France
Phone: (33) 1 46 54 78 62
Fax: (33) 1 47 46 97 77
E-mail: jeanfrancois.bottollier@ipsn.fr

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The assessment of exposure to cosmic radiation on board air craft is one of the preoccupations of organisations responsible for radiation protection. Cosmic particles flux increases with altitude and latitude and depends on the solar activity. The exposure has been estimated on several airlines using transatlantic, Siberian and transequatorial routes on board subsonic and supersonic air crafts, to illustrate the effect of these parameters. Measurements have been realised with a tissue equivalent proportional counter using the microdosimetric technique. Such a system provides the absorbed dose, the ambient dose equivalent, the mean quality factor and the dose distribution as a function of lineal energy. Data have been collected at maximum solar activity in 1991-92 and at minimum in 1996-98. The lowest mean dose rate measured was 3 μSv.h^{-1} during a Paris-Buenos Aires flight in 1991; the highest was 6.6 μSv.h^{-1} during a Paris-Tokyo flight using a Siberian route and 9.7 μSv.h^{-1} on Concorde in 1996-97. The mean quality factor is around 1.8. The corresponding annual effective dose, based on 700 hours of flight for subsonic aircraft and 300 hours for Concorde, can be estimated between 2 mSv for least-exposed routes and 5 mSv for more exposed routes.

INTRODUCTION

The study of naturally-occurring radiation and its effects on man is one of the preoccupations of organisations responsible for radiation protection. For several ten years, space programmes have been supported to assess the dose received by astronauts during a space mission. Some of the dosimetric systems developed for studies in space have been used to measure the doses received by flight crew on long-haul flights.

Cosmic particle flux increases with latitude and altitude. It is significantly higher on board aircraft than at ground level. The complexity of the radiation field does not make dose measurement easy and indeed, the particles encountered vary considerably, with a wide range of energy. The gravity of the consequences for biological structures depends on the energy. Therefore, if the effective dose is to be estimated, the absorbed dose has to be known, along with the radiation weighting factor.

Several airlines were selected to illustrate the effect of various parameters such as altitude, latitude and flight time. Measurements were planned for different periods of the year so that the effects of solar activity can be assessed. This study gives the results of measurements made during the period 1996-98, when solar activity was at its lowest, on five routes out of Paris: Tokyo, San Francisco, Buenos Aires, Washington and New York (on Concorde). The results are compared to those obtained in 1991-92 when solar activity was at a peak.

COSMIC RADIATION

The cosmic radiation on which radiation protection focuses is comprised at the outset of charged particles (ions and electrons) and secondary particles resulting from their interaction with the atmosphere (ions, neutrons, gamma rays, electrons etc.).

Primary cosmic radiation mainly consists of the nuclei of atoms which have lost their electrons due to their extremely high velocity; these charged particles are hydrogen nuclei (protons), helium nuclei (alpha particles) and the nuclei of heavier elements such as iron and nickel; there are also some electrons (1%) and positrons (1‰). One stable component is due to galactic and extra-galactic radiation; it comprises ions whose energy value can reach 10^{20} electronvolts, averaging out at a few 10^9 electronvolts. The other component comes from the sun and is known as solar wind; it fluctuates with solar eruptions which produce large quantities of particles, mainly protons. The atomic number and energy value of particles of solar origin are generally lower than those of the galactic and extra-galactic component. Average solar activity occurs over an 11-year cycle (1-2).

The charged particles move around and interact with the interstellar magnetic field and, for our purposes, with the terrestrial magnetic field to form the magnetosphere. The particles exercise widespread pressure on the magnetic field on the side exposed to the sun and produce a magnetospheric tail at the rear. This perturbation is considerable at high altitudes. At altitudes below a few earth radii (a radius is equal to 6370 km), the dipolar structure of the magnetic field predominates; this phenomenon explains the presence of polar cones centred around the magnetic poles where the magnetic field offers less resistance to incoming charged particles. There are belts of charged particles, known as Van Allen belts, corresponding to a drop in pressure of the magnetic field in which the charged particles are trapped. Generally speaking, there are two belts beyond a few hundred kilometres, depending on the type of particles. The first belt is made up of electrons and the second, larger belt of protons. The environment fluctuates with the flow of cosmic particles, particularly during solar eruptions. These perturbations, which can be considerable, may cause magnetic storms and the injection of particles into the belts close to the magnetic poles (1-2).

The particles making up the cosmic radiation also interact with interstellar gas and, closer to the earth, with the atmosphere. Secondary particles (neutrons, ions, electrons, gamma rays, muons etc.) are produced by the break up of cosmic ions and atoms of interstellar and atmospheric gas. A similar process occurs in aircraft skins.

Because of the magnetic field and the atmosphere, only the most energetic ions, mainly those contained in galactic cosmic radiation, reach low altitudes where they interact. This galactic component is modulated by the solar wind outside the magnetosphere, being more heavily influenced when there is considerable solar activity. These phenomena explain why the flow of cosmic particles at ground level is lowest when solar activity is at a peak and vice versa. Figure 1 illustrates solar activity and the changes in cosmic particle flux at ground level (Data provided by P. Lantos, Paris-Meudon Observatory).

The magnetosphere and the atmosphere together form a powerful shield protecting us from cosmic rays. Without it, the dose received on the earth's surface would exceed 1 Sv.year^{-1}.

MEASUREMENT APPARATUS

The device used to take the measurements, NAUSICAA, was developed for estimating the doses received by astronauts (3). A sample operated on board the Mir space station for three and a half years (4). Portable versions are used in other situations, particularly aboard aircraft and in radiation facilities (5).

The detector is a Tissue Equivalent Proportional Counter (TEPC), considered by specialists as the reference detector for measuring doses from cosmic radiation (6). It is sensitive to directly ionising particles (ions, electrons and gamma rays) as well as to neutrons via the charged secondary particles created by them in the walls of the counter. The sensitive volume is a 5x5 cm cylinder filled at low pressure (33 hPa) with a gas « equivalent » to biological tissue. This gas is based on propane: 50% C_3H_8, 40% CO_2 and 5% N_2. The detector simulates a 3 micron-long biological site located inside the organism at a depth of 1 cm.

Incident radiation produces a quantity of electrons in the gas proportional to the amount of energy deposited. Each event detected is analysed using a pulse height analysis method (PHA) and stored to produce the lineal energy distribution spectrum, y; y is the energy deposited over the average chord of the detector. The system uses a logarithmic amplifier because of the dynamic range of y (10^4) and a 256 multi-channels analyser. There is a relation between y and the linear energy transfer (LET) which is related to the quality factor (Q). The sum of all events provides the absorbed dose (D), an assessment of the ambient dose equivalent (H*(10)) and the average quality factor (Q = H*(10)/D) of the radiation. An internal source of alpha particles (^{244}Cm) is used to adjust the high voltage of the system. The ambient dose equivalent calibration is done with a ^{60}Co source for LET lower than 4 keV/µm and with a AmBe neutron source for higher LET.

RESULTS

The results given are those obtained from measurements made in 1996-98; they will be compared to the 1991-92 results (7) to assess the effect of solar activity. Take-off and landing periods are taken into account when calculating doses received during flights and average dose rates. The ambient dose equivalent is calculated using the quality factor-LET relationship given in ICRP 60 (8); the values are usually 20% higher than those obtained with ICRP 26 (9). Since the irradiation of individuals is uniform, it is our opinion that the ambient dose equivalent value estimated by the measurements is a reasonable approximation, albeit overestimated at times, of the effective dose value. Moreover, since we are dealing with extremely penetrating radiation, the value of the average quality factor (Q) obtained from the experiment is a reasonable approximation of the radiation weighting factor (W_R).

The measurements, lasting 5 to 15 minutes, depending mainly on altitude, were made continuously on all the flights. The NAUSICAA device was installed in the flight deck on subsonic flights and in the cabin on Concorde. The Paris-Buenos Aires flight was not taken into consideration because certain measurements were affected by the aircraft instrumentation system; data obtained during the return flight could be used for the outward trip since the two routes were comparable. The error on measurements during a flight is lower than ±20 %.

Figure 2 shows a map giving an overview of the ambient dose equivalent for the various flights during the period 1996-98. The maximum integrated dose, 150 µSv, is for the round trip Paris - Tokyo and San Francisco; for Buenos Aires, the longest flight, the dose is 30 % lower (100 µSv). The dose received for the round trip Paris - Washington (14.6 hours) is comparable to the one for New York with Concorde (7 hours); this comparison points out the effect of altitude (up to 18,000 metres for Concorde). The Figure 3 gives the ambient dose equivalent and the absorbed dose rate profiles measured for three flights and the effective dose rate calculated[1] with the code CARI-5E (10), developed by the Federal Aviation Administration (USA). The dose rates increase with the flight level, this dependence is obvious for the absorbed dose rate. There are considerable local variations in ambient dose equivalent at times due to high LET events (> 10 keV.µm^{-1}) which have a significant effect in terms of dose but a lower probability of occurrence than low LET events. Doses distributions as a function of lineal energy (Fig. 4) show two distinct parts, the first one under 10 keV.µm^{-1} corresponding to low LET events and the second one above due mainly to secondary particles, i.e. protons, created by neutrons.

Tables I gives the flight parameters and the average dose rates obtained from measurements made in 1996-98. The neutron contribution estimated from the previous dose distributions can be assessed between 40 % and 50 % of the total ambient dose equivalent.

The mean quality factor is around 1.8. A comparison with the 1991-92 measurements is presented in Table II. The ambient dose equivalent rates at the maximum of solar activity are between 15 % and 40 % lower than those measured during the minimum phase.

The annual ambient dose equivalent is estimated for each route on the basis of 700 hours for subsonic flights and 300 hours for supersonic flights (Table III). These values are probably overestimated because the number of flight hours registered for each crew member is taken « block-block ».

DISCUSSION

As expected, the lowest average dose rates for long-haul flights are observed on routes close to the equator and when solar activity is at a peak (minimum amount of cosmic radiation at ground level); for example, in the period 91-92 on the Paris-Buenos Aires flight, the average rate throughout the flight was around 3 $\mu Sv.h^{-1}$.

At higher latitudes and when the solar activity is lower, the values are higher; for the Paris-Tokyo flight passing over Siberia, the average dose rate measured in 97 was 6.6 $\mu Sv.h^{-1}$. For the cargo flight between Tokyo and Paris passing over the North Pole with a stop at Fairbanks, the average dose rate was 5 $\mu Sv.h^{-1}$. On polar routes at a given altitude, the cosmic radiation flow can generally be compared to that of Siberian routes and indeed beyond a geomagnetic latitude of 65°, it is taken as being constant. The measured value is lower than on Siberian routes because the average altitude is lower. As far as supersonic flights are concerned, the dose levels are far higher due to altitude (up to 18,000 metres); throughout the Paris-New York flight during a period of low solar activity, the average rate was approximately 9.5 $\mu Sv.h^{-1}$. Overall flights, the agreement between the average experimental dose equivalent rate and the average effective dose rate given by CARI-5E is better than 15 %, the experimental values being higher than the calculated ones.

For comparison, the equivalent dose rates as a function of the flight altitude, for geomagnetic latitudes higher than N50°, obtained from measurements done in 1996-98 (Fig. 5) are coherent with those given by G. Reitz (1) for the minimum solar activity. They are higher than those published by R. Regulla and J. David (11) by about 20 % and those calculated by CARI-5E by 15 % maximum. A comparison with results obtained with other TEPC's on flights between Europe and USA shows that the equivalent dose rate measured agrees within ± 20 % (12).

The major events associated with solar eruptions may occasionally lead to far higher doses. The dose received by the passengers on a flight at 10,000 m at high latitude during the largest solar eruption to date (1956) can be estimated at more than 10 mSv (13). Fortunately, events such as this are very rare and of short duration (a few hours). It is therefore highly unlikely that any one individual, even a member of the flight crew, could receive several times in his life a dose of this size.

CONCLUSION

Ambient measurements taken on board long-haul flights can be used to assess an annual effective dose equivalent range, based on 700 hours of flight: between 2 mSv for the least-exposed long-haul flights at low latitude and with maximum solar activity, for example Buenos Aires and should not exceeded 5 mSv for more-exposed routes at high latitude and with minimum solar activity, for example Paris-Tokyo by Siberian or polar route or Paris-San Francisco. The value on board Concorde falls within this range since the annual number of hours in the air is lower (300 hours).

These values are clearly above the limits recommended for the public (1 $mSv.year^{-1}$) by the International Commission on Radiological Protection (ICRP) in 1991. For European countries, the directive of 13 May 1996 (14) sets basic standards and the rules to protect the health of the public and workers from the dangers of ionising radiation on the basis of ICRP recommendations. The directive asks operating organisations to assess flight crew exposure whenever it exceeds 1 $mSv.year^{-1}$. Doses received by each crew member should be recorded for each flight and sum over a year and more. Using appropriate computer programme and data file, personal exposure could be assessed if the various routes taken by individuals were known, along with the corresponding dates. The reliability of this kind of approach has yet to be validated .

ACKNOWLEDGEMENTS

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FOOTNOTES

[1] Calculations done in collaboration with P. Lantos and N. Fuller from the Paris-Meudon Observatory.

FIG. 1. Solar activity cycle (No. 22) given by the sun spot index and changes in cosmic radiation at ground level based on flow measurement of secondary neutrons created in the atmosphere (Kergelen station) (3). The cosmic radiation at low altitude is maximum when the solar activity is minimum and vice versa.

FIG. 2. Route map for flights between 1996 and 1998 and the corresponding ambient dose equivalent rate, mean rate and cumulated over the flight and the mean quality factor.

FIG. 3. Profile of ambient dose equivalent rate (H*(10)), absorbed dose rate (D) and altitude for Paris-New York with Concorde (21/08/96), Tokyo-Fairbanks-Paris with a cargo flight B747-200 (30/01/97) and Paris-Washington with a B747-400 (22/01/98). Comparison with the effective dose rate (E) calculated with the code CARI-5E.

FIG. 4. Absorbed dose and equivalent dose distribution as function of lineal energy for Paris-San Francisco with a A340 (04/04/96) and Paris-New York with Concorde (21/08/96). The part above 10 keV/µm provides from neutrons mainly.

FIG. 5. Ambient dose equivalent rates as a function of the flight altitude, using the Q function according to ICRP60, for geomagnetic latitudes higher than N50°. Comparison with Reitz's (1) and Regulla's data (12) and CARI-5E calculations .

TABLE I
Flight parameters and average dose rates obtained from measurements made in 1996-98.

Route and date	Flight duration (h)	Mean altitude (m)	Total equivalent dose rate ($\mu Sv.h^{-1}$)	Total absorbed dose rate ($\mu Gy.h^{-1}$)	Neutron equivalent dose part (%)	Mean quality factor
Paris-Tokyo (Siberian route)						
(B747-400) 27/01/97	11.5	10700	6.6	3.6	45	1.8
Tokyo-Fairbanks-Paris (Polar route)						
(Cargo B747-200) 30/01/97	14.9	10100	5.0	2.7	45	1.8
Paris-San Francisco						
(A340) 03/04/96	11.4	11100	6.4	3.5	45	1.8
San Francisco-Paris						
(A340) 04/04/96	10.8	10600	6.3	3.5	44	1.8
Paris-Washington						
(B747-400) 22/01/98	7.3	10200	6.1	3.4	45	1.8
Buenos Aires-Paris						
(A340) 03/04/96	12.3	10300	4.3	2.5	44	1.7
Paris-New York						
(Concorde) 21/08/96	3.6	15400	9.7	5.8	41	1.7
New York-Paris						
(Concorde) 22/08/96	3.4	15000	9.2	5.7	42	1.6

TABLE II
Comparison of the 1996-1998 measurements made during the minimum solar activity with the 1991-92 measurements made during the maximum solar activity.

Route	Mean equivalent dose rate ($\mu Sv.h^{-1}$)	
	1991-1992	1996-1998
Paris-Tokyo (Siberian route)	6.5	6.6
Buenos Aires - Paris	3.0	4.3
Paris-New York (Concorde)	8.6	9.5 [a]

[a] Mean value of the two flights.

TABLE III

Annual effective dose estimated on the basis of 700 hours for subsonic flights and 300 hours for supersonic flights during minimum and maximum solar activity.

Route	Annual effective dose (mSv)	
	1991-1992	1996-1998
Paris-Tokyo (Siberian route)	4.6	4.6
Paris-San Francisco-Paris	-	4.4
Paris-Washington	-	4.3
Buenos-Aires	2.1	3.0
Paris-New York (Concorde)	2.6	2.8